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# Assessment of meta-modeling knowledge: Learning from triadic concepts of models in the philosophy of science

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**Abstract**
Meta-modeling knowledge is an established construct in science education, typically conceptualized in frameworks encompassing hierarchically ordered levels of understanding specific for different aspects (e.g., purpose of models, testing models, changing models). This study critically discusses the appropriateness of assessments based on such frameworks taking into account triadic concepts of models in the philosophy of science. Empirically, secondary school students' ($N$=359) responses to modeling tasks are analyzed. In the tasks, the modeling-purpose is not subject of the assessment, but intentionally provided. The findings show that students' expressed level of understanding significantly depend on both the modeling-purpose and the modeling-context introduced in the tasks. Implications for science education are discussed.

**Keywords**
meta-modeling knowledge; assessment; context-dependency; levels of understanding

## Theoretical background and aim of the study

Models and modeling are of significant importance for communication and reasoning in science (e.g., Giere, Bickle, & Mauldin, 2006; Odenbaugh, 2005). Models can be conceptualized both rather statically as a form of knowledge representation and – more dynamically – as research tools for scientific discovery (Gouvea & Passmore, 2017; Krell & Krüger, 2017). The process of scientific modeling involves the selection of parts or variables of a system which are considered to be important in a given context and, therefore, should be incorporated in a model (Bailer-Jones, 2003; Giere et al., 2006). Therefore, no model is complete or totally accurate, but pragmatically useful (Odenbaugh, 2005). It depends on the modeler's (the cognitive agent's; Giere, 2010) intention, that is the purpose of modeling, which specific features a model will or should have. Therefore, Bailer-Jones (2003) states that 'whether a model is suitable or not can be only decided once the model's function is taken into account' (pp. 70-71). According to these thoughts, most contemporary concepts of models in science are called '(at least) triadic' and include, next to the model and the thing or process which is modelled (i.e. 'dyadic'), an intentionally modeling cognitive agent (Knuuttila, 2005); for example: 'Model $M$ is an entity used by agent $A$ to represent target system $S$ for purpose $P$' (Mäki, 2005, p. 305; cf. Giere, 2010). Triadic conceptions of models are a theoretical 'shift away' from conceptions 'according to which representation is a dyadic relation between two things' (Knuuttila, 2005, p. 1261). Hence, the various contexts and purposes of modeling in science and its pragmatic and creative dimensions are considered in triadic conceptions of models (Bailer-Jones, 2003; Odenbaugh, 2005).

Modeling is also seen as a key process in science education (e.g., Gouvea & Passmore, 2017; Upmeier zu Belzen & Krüger, 2010) and the promotion of meta-modeling knowledge, as a part of scientific meta-knowledge, is seen as one goal of science education (Krell & Krüger, 2017; Schwarz et al., 2009). Meta-modeling knowledge is usually defined as 'a type of nature of science understanding', which includes knowledge about 'how models are used, why they are used, and what their strengths and limitations are, in order to appreciate how science works and the dynamic nature of knowledge that science produces' (Schwarz et al., 2009, pp. 634–635).

The development of theoretical frameworks for the operationalization of meta-modeling knowledge (e.g., competence models, learning progressions; Upmeier zu Belzen, Alonzo, Krell, & Krüger, in press) and appropriate assessment instruments became an integral part of science education research (Mathesius & Krell, in press). Table 01 exemplarily illustrates that recent frameworks for meta-modeling knowledge in science education typically encompass hierarchically ordered levels of understanding specific for different aspects of meta-modeling knowledge and value the understanding of models as research tools higher than the understanding of models as knowledge representations (cf. Crawford & Cullin, 2005; Everett, Otto, & Luera, 2009; Upmeier zu Belzen & Krüger, 2010).

However, taking triadic approaches of models in science into account, the notion of hierarchically ordered levels of meta-modeling knowledge can be criticized, for example:

1) The scoring of the view of the purpose of models to describe or to explain something as a lower level understanding representing a 'limited' or 'pre-scientific' view (Crawford & Cullin, 2005, p. 316) can be questioned since philosophers of science argue that models have various purposes, including communicative and explanatory ones (Giere et al., 2006; Odenbaugh, 2005).

2) The modeling-purpose should be taken into account to meaningfully judge a given model's appropriateness (Bailer-Jones, 2003). For instance, it is quite reasonable to compare a model with what is already known about a phenomenon (e.g., testing models, level II; Table 01) when the modeling-purpose is knowledge representation.

3) Basically, the notion of hierarchically ordered levels of meta-modeling knowledge suggests, at least implicitly, a higher educational value of views described in higher levels, which stays in contrast to the various purposes and pragmatic approaches of modeling in science (Bailer-Jones, 2003; Odenbaugh, 2005).

Based on the considerations above, this study explores students' meta-modeling knowledge using tasks with the modeling-purpose not being subject of the assessment, but intentionally provided in the task. The following research question was guiding the study:

*To what extent does secondary school students' expressed meta-modeling knowledge differ depending on different modeling-purposes, which are described in the tasks?*

Table 01. A framework with aspect-specific levels of meta-modeling knowledge

| Aspects | Level I | Level II | Level III |
|---|---|---|---|
| **Framework for model competence** (Upmeier zu Belzen & Krüger, 2010) | | | |
| **Purpose of models** | Describing the original | Explaining the original | Predicting something about the original |
| **Testing models** | Testing the model object | Compare the model and the original | Testing hypotheses about the original |
| **Changing models** | Correcting defects of the model object | Revise due to new insights | Revise due to the falsification of hypotheses about the original |

*Note*: The framework includes further aspects. The level descriptions have been shortened.

### Instrument for data collection

Tasks to assess students' understanding of the two aspects *testing models* and *changing models* (Table 01) have been developed based on a facetted test design with the dimensions *modeling-context, purpose of modeling, aspect of meta-modeling knowledge,* and l*evel of understanding* (Tables 01, 02). For each level of understanding, a short description ('item') has been specifically phrased for the three modeling-contexts. The systematic combination of the dimensions resulted in 3 x 3 x 2 x 3 = 54 items in total (Appendix, Table 04). The students in this study were asked to judge whether the items (e.g., descriptions of levels I, II, and III in the aspect testing models; Appendix, Figure 02) are appropriate in the given context and for the given modeling-purpose (yes/no questions). Hence, a judgement on items are interpreted as an indicator for the students' meta-modeling knowledge, as it is done in several other studies in science education (cf. Mathesius & Krell, in press).

The tasks have been developed based on an abstract template that provides elements each task should include (e.g., description of an authentic modeling-context, description of a modeling-purpose, illustrative figures; cf. Appendix, Figure 02). The tasks have been analyzed, critically discussed and optimized by science education researchers with expertise in models and modeling as well as assessment in science education. In a subsequent pilot study, secondary school students answered the tasks and provided comments about unclear terms, expressions, and other problems they had in understanding the tasks. These comments were taken into account as well to optimize the tasks.

For the present study, the final tasks have been systematically arranged within twelve different test booklets. The tasks have been arranged in the test booklets in a way that 1) each test booklet includes three tasks, that is nine items to be judged, 2) each test booklet includes one task for each modeling-context, 3) each test booklet includes tasks related to both aspects *testing models* and *changing models*, 4) each task is included in two test booklets (cf. Appendix, Table 04).

### Sample

Secondary school students ($N$ = 359) from public schools in Germany voluntarily agreed to participate in this study (accidental sampling, school years 9 to 10, mean age 16 years). The students did not receive any specific teaching on models and modeling prior to the assessment. The twelve test booklets were answered by between 25 and 33 students. Testing time was about 15 minutes.

### Data analysis

It was recorded whether the students chose 'yes' (=1) or 'no' (=0) in the items. A (three-way) ANOVA was conducted with the item features introduced modeling-purpose, modeling-context, and level of understanding as independent variables and the mean agreement with each item (i.e., 'yes') as dependent variable.

### Findings

The three-way ANOVA results in two significant interaction effects with large effect sizes (Table 03, see next page).

The agreement with level II varies less between the three modeling-purposes than the agreements with levels I and III (Figure 01, left). A simple effects analysis reveals that there are no significant differences between the agreements with level II for the three modeling-purposes. The students agreed with level I significantly more often when an aesthetic modeling-purpose was introduced ($M$=.616) than when a re-

Table 02. Description of the dimensions *modeling-context* and *modeling-purpose* (see Table 01 for *aspect of meta-modeling knowledge* and *level of understanding*)

| | | | |
|---|---|---|---|
| **Modeling-context** | Computer modeling of a fossil called Alienopterus (cf. Bai et al., 2018) | Development of a model of the Brachiosaurus (cf. Taylor, 2009) | Mathematical modeling of an Ebola epidemic (cf. Dobson, 2014) |
| **Modeling-purpose** (cf. Mahr, 2011) | Aesthetic purpose to produce decorative or depictive objects (cf. Mahr, 2011) | Representative purpose to produce knowledge representations | Research purpose to discover phenomena |

Table 03. Results of the ANOVA with level of understanding, modeling-purpose and modeling-context as independent variables and the agreement with the levels as dependent variable ($R^2$=.820)

| | *SS* | *df* | *MS* | *F* | *p* | **partial η²** |
|---|---|---|---|---|---|---|
| Level | .257 | 2 | .128 | 20.029 | .000 | .597 |
| Purpose | .050 | 2 | .025 | 3.923 | .032 | .225 |
| Context | .035 | 2 | .018 | 2.741 | .082 | .169 |
| Level x purpose | .270 | 4 | .067 | 10.526 | .000 | .609 |
| Level x context | .103 | 4 | .026 | 4.018 | .011 | .373 |
| Purpose x context | .007 | 4 | .002 | .281 | .888 | .040 |
| Level x purpose x context | .066 | 8 | .008 | 1.294 | .288 | .277 |
| Error | .173 | 27 | .006 | | | |
| Total | 21.737 | 54 | | | | |

search purpose (*M*=.480) was introduced in the task (*p*=.006). For level III, agreement occurred more often when a representative (*M*=.642; *p*<.001) or a research purpose (*M*=.718; *p*<.001) was introduced, compared to an aesthetic purpose (*M*=.438). There are no significant differences between the agreements to levels II and III for the different modeling-contexts (Figure 01, right). For level I, the students agreed significantly more often in the Brachiosaurus context (*M*=.650) than in the Alienopterus (*M*=.505; *p*=.004) and the Ebola context (*M*=.491; *p*=.002).

## Summary and discussion

As discussed in the theoretical background of this article, the established approach in science education research is to treat meta-modeling knowledge as a construct comprising different aspects and hierarchically ordered levels of understanding (e.g., Crawford & Cullin, 2005; Everett et al., 2009; Upmeier zu Belzen & Krüger, 2010; cf. Table 01). Clearly, this approach contributed to grasp the nature of meta-modeling knowledge in science education. For example, research findings widely show that for most sample groups it seems to be quite diffi-

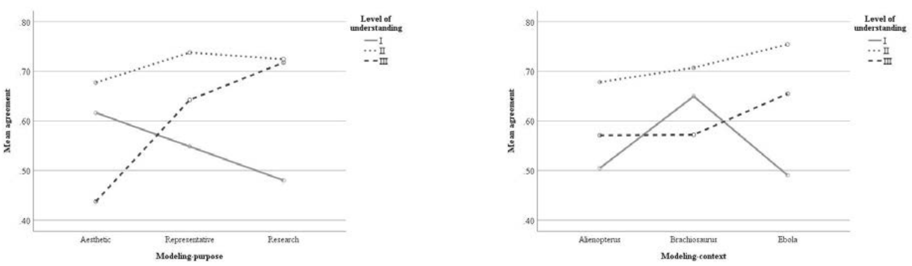



*Figure 01*. Interaction graphs representing the significant interaction effects introduced modeling-purpose x level of understanding (left) and modeling-context x level of understanding (right) on the students' agreement

cult to understand the role of models as research tools (e.g., Crawford & Cullin, 2005; Krell & Krüger, 2017); possibly because this contradicts the way models have been experienced in daily life (e.g., at school; Krell, Reinisch, & Krüger, 2015). Consequently, it is proposed to emphasize the nature of models as theoretical entities and research tools in educational settings (Gouvea & Passmore, 2017). However, the notion of hierarchically ordered levels of understanding can be criticized as well. To address these criticisms, it is proposed in this article to treat meta-modeling knowledge in line with triadic concepts of models in science as a context-dependent construct (cf. Krell, Upmeier zu Belzen, & Krüger, 2014; Leach, Millar, Ryder, & Séré, 2000).

The findings of this study illustrate that students' meta-modeling knowledge can significantly differ, dependent on the given modeling-context and the introduced modeling-purpose (Figure 01). The findings suggest that an understanding of models as research tools may exist within students, but is more likely expressed in appropriate contexts, describing appropriate modeling-purposes. However, albeit the students – in tendency – seemed to be aware of the purpose-dependency of models in science, the view of models as representational entities (i.e., level II) was still dominant (Figure 01).

There are some limitations of this study. First, three authentic modeling-contexts have been used to develop the tasks in this study. As studies revealed that students' meta-modeling knowledge is also likely to depend on the concrete model, which is described in a task (Krell et al., 2014), future studies may use a larger set of tasks in order to systematically investigate the effect of the provided modeling-purpose, the concrete model and other factors (e.g., the scientific discipline; Krell et al., 2015) – considering interaction effects between these factors as well. Second, future studies may also include a balanced sample of different subgroups like primary school students, secondary school students and university students in order to investigate to what extent the purpose-dependency in students' meta-modeling knowledge depends on the educational level. Third, this study exemplarily investigated the effects different modeling-purposes on students' views about *testing models* and *changing models* (Table 01), but there are further important aspects of meta-modeling knowledge proposed in the literature, for example nature of models and multiple models (e.g., Crawford & Cullin, 2005; Upmeier zu Belzen & Krüger, 2010). Fourth, this study explored to what extent students' meta-modeling knowledge differs depending on different modeling-purposes. Further studies may also explore experts' views in order to provide a 'standard' with which the students' views may be compared.

**Implications**

The findings of this study propose that students are able to understand models as research tools (Gouvea & Passmore, 2017); but that this understanding is more likely to be expressed within appropriate contexts and especially within appropriate modeling-purposes. It is proposed to consider such context-dependencies in assessments and – as a challenging task for science education research – to explain them in order to develop theoretical frameworks with explanatory and predictive power about how students' epistemic knowledge varies across the diverse contexts science comprises.

Albeit not being the focus of the present study, the findings may have implications for teaching and learning as well. Leach et al. (2000) argue that teaching of situated and contextualized constructs might best be understood as a process of enculturation (opposed to 'teaching for conceptual change'; p. 501), in which the range of possible views and appropriate contexts are discussed. Following this argument, teaching and learning meta-modeling knowledge might best be described as discussing the various contexts and purposes of modeling in science, in order to appreciate the wide range of appropriate modeling strategies, as well as the diverse and context-dependent ways to test and change models in science.

## References


Bai, M., Beutel, R., Zhang, W., Wang, S., Hörnig, M., Gröhn, C., …Wipfler, B. (2018). A new cretaceous insect with a unique cephalo-thoracic scissor device. *Current Biology, 28*, 438-443.e1. doi:10.1016/j.cub.2017.12.031

Bailer-Jones, D. (2003). When scientific models represent. *International Studies in the Philosophy of Science, 17*, 59–74.

Crawford, B., & Cullin, M. (2005). Dynamic assessments of preservice teachers' knowledge of models and modelling. In K. Boersma, M. Goedhart, O. de Jong, & H. Eijkelhof (Eds.), *Research and the quality of science education* (pp. 309–323). Dordrecht: Springer.

Dobson, A. (2014). Epidemiology: Mathematical models for emerging disease. *Science, 346*, 1294–1295. doi:10.1126/science.aaa3441

Everett, S., Otto, C., & Luera, G. (2009). Preservice elementary teachers' growth in knowledge of models in a science capstone course. *International Journal of Science and Mathematics Education, 7*, 1201–1225.

Giere, R. (2010). An agent-based conception of models and scientific representation. *Synthese, 172*, 269–281.

Giere, R., Bickle, J., & Mauldin, R. (2006). *Understanding scientific reasoning*. London: Thomson Learning.

Gouvea, J., & Passmore, C. (2017). 'Models of' versus 'Models for'. *Science & Education, 26*, 49–63. doi:10.1007/s11191-017-9884-4

Knuuttila, T. (2005). Models, representation, and mediation. *Philosophy of Science, 72*, 1260–1271.

Krell, M., & Krüger, D. (2017). University students' meta-modelling knowledge. *Research in Science & Technological Education, 35*, 261–273. doi:10.1080/02635143.2016.1274724

Krell, M., Reinisch, B., & Krüger, D. (2015). Analyzing students' understanding of models and modeling referring to the disciplines biology, chemistry, and physics. *Research in Science Education, 45*, 367–393. doi:10.1007/s11165-014-9427-9

Krell, M., Upmeier zu Belzen, A., & Krüger, D. (2014). Context-specificities in students' understanding of models and modelling: An issue of critical importance for both assessment and teaching. In C. Constantinou, N. Papadouris, & A. Hadjigeorgiou (Eds.), *E-Book proceedings of the ESERA 2013 conference. Science education research for evidence-based teaching and coherence in learning* (pp. 41–52). Nicosia, Cyprus: European Science Education Research Association. Retrieved from https://www.esera.org/publications/esera-conference-proceedings/esera-2013

Leach, J., Millar, R., Ryder, J., & Séré, M.-G. (2000). Epistemological understanding in science learning: The consistency of representations across contexts. *Learning and Instruction, 10*, 497–527.

Mahr, B. (2011). On the epistemology of models. In G. Abel & J. Conant (Eds.), *Rethinking epistemology* (pp. 301–352). Berlin, Boston: De Gruyter.

Mäki, U. (2005). Models are experiments, experiments are models. *Journal of Economic Methodology, 12*, 303–315.

Mathesius, S., & Krell, M. (in press). Assessing model competence with questionnaires. In A. Upmeier zu Belzen, D. Krüger, & J. van Driel (Eds.), *Towards a competence-based view on models and modeling in science education*. Springer.

Odenbaugh, J. (2005). Idealized, inaccurate but successful: A pragmatic approach to evaluating models in theoretical ecology. *Biology & Philosophy, 20*, 231–255.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Achér, A., Fortus, D., …Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*, 632–654.

Taylor, M. (2009). A re-evaluation of Brachiosaurus altithorax Riggs 1903 (Dinosauria, Sauropoda) and its generic separation from Giraffatitan brancai (Janensch 1914). *Journal of Vertebrate Paleontology, 29*, 787–806.

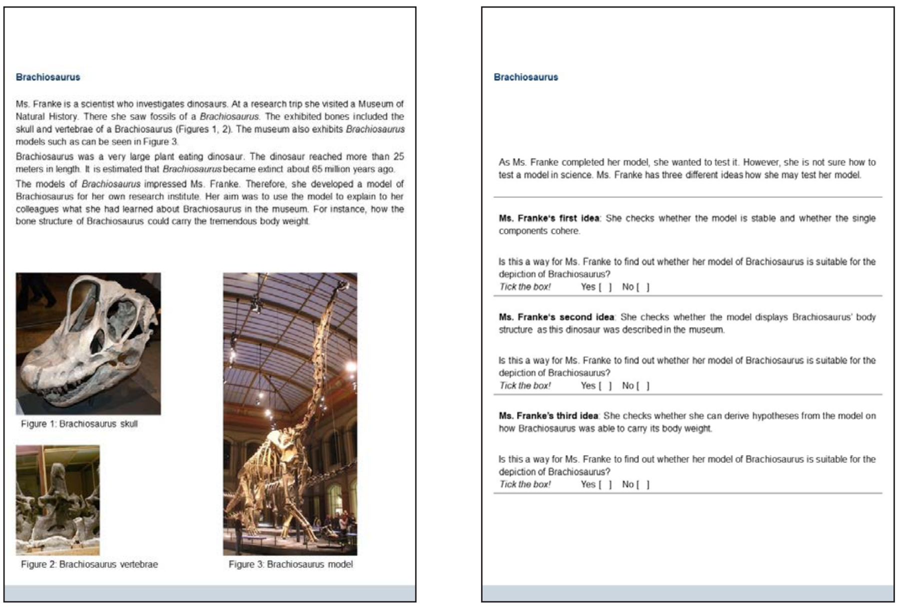
Upmeier zu Belzen, A., Alonzo, A., Krell, M., & Krüger, D. (in press). Learning progressions and competence models: A comparative analysis. In McLoughlin, E., Finlayson, O.E., Erduran, S., Childs, P. (Eds.), *Bridging research and practice in science education*. Springer.

Upmeier zu Belzen, A., & Krüger, D. (2010). Modellkompetenz im Biologieunterricht [Model competence in biology teaching]. *Zeitschrift für Didaktik der Naturwissenschaften, 16*, 41–57. Retrieved from http://www.ipn.uni-kiel.de/zfdn/pdf/16_Upmeier.pdf

## Appendix

Table 04. Facetted test design for the systematic development of 54 tasks (in grey: task in Figure 02)

| Modeling-context | Purpose of modeling | Aspect of meta-modeling knowledge | Level of understanding | Included in test booklets no. |
|---|---|---|---|---|
| Alienoptera | Aesthetic | Testing models | I, II, III | 1, 10 |
| | | Changing models | I, II, III | 4, 7 |
| | Representative | Testing models | I, II, III | 2, 11 |
| | | Changing models | I, II, III | 5, 8 |
| | Research | Testing models | I, II, III | 3, 12 |
| | | Changing models | I, II, III | 6, 9 |
| Brachiosaurus | Aesthetic | Testing models | I, II, III | 3, 9 |
| | | Changing models | I, II, III | 6, 12 |
| | Representative | Testing models | I, II, III | 1, 7 |
| | | Changing models | I, II, III | 4, 10 |
| | Research | Testing models | I, II, III | 2, 8 |
| | | Changing models | I, II, III | 5, 11 |
| Ebola | Aesthetic | Testing models | I, II, III | 5, 8 |
| | | Changing models | I, II, III | 2, 11 |
| | Representative | Testing models | I, II, III | 6, 9 |
| | | Changing models | I, II, III | 3, 12 |
| | Research | Testing models | I, II, III | 4, 7 |
| | | Changing models | I, II, III | 1, 10 |



**Brachiosaurus**

Ms. Franke is a scientist who investigates dinosaurs. At a research trip she visited a Museum of Natural History. There she saw fossils of a *Brachiosaurus*. The exhibited bones included the skull and vertebrae of a Brachiosaurus (Figures 1, 2). The museum also exhibits *Brachiosaurus* models such as can be seen in Figure 3.

Brachiosaurus was a very large plant eating dinosaur. The dinosaur reached more than 25 meters in length. It is estimated that *Brachiosaurus* became extinct about 65 million years ago.

The models of *Brachiosaurus* impressed Ms. Franke. Therefore, she developed a model of Brachiosaurus for her own research institute. Her aim was to use the model to explain to her colleagues what she had learned about Brachiosaurus in the museum. For instance, how the bone structure of Brachiosaurus could carry the tremendous body weight.

Figure 1: Brachiosaurus skull

Figure 2: Brachiosaurus vertebrae

Figure 3: Brachiosaurus model

**Brachiosaurus**

As Ms. Franke completed her model, she wanted to test it. However, she is not sure how to test a model in science. Ms. Franke has three different ideas how she may test her model.

**Ms. Franke's first idea**: She checks whether the model is stable and whether the single components cohere.

Is this a way for Ms. Franke to find out whether her model of Brachiosaurus is suitable for the depiction of Brachiosaurus?
*Tick the box!* Yes [ ] No [ ]

**Ms. Franke's second idea**: She checks whether the model displays Brachiosaurus' body structure as this dinosaur was described in the museum.

Is this a way for Ms. Franke to find out whether her model of Brachiosaurus is suitable for the depiction of Brachiosaurus?
*Tick the box!* Yes [ ] No [ ]

**Ms. Franke's third idea**: She checks whether she can derive hypotheses from the model on how Brachiosaurus was able to carry its body weight.

Is this a way for Ms. Franke to find out whether her model of Brachiosaurus is suitable for the depiction of Brachiosaurus?
*Tick the box!* Yes [ ] No [ ]

*Figure 02.* Left: The Brachiosaurus modeling-context with a representative modeling-purpose described in the third paragraph. For the other tasks with the same context, the third paragraph was replaced by a description of an aesthetic or a research modeling-purpose, respectively. Right: The three items representing level I ('Ms. Franke's first idea'), level II ('Ms. Franke's second idea'), and level III ('Ms. Franke's third idea') of the aspect testing models. Note that the original version of the tasks is in German language and linguistic flaws may be caused by the translation. (Figures 1, 3 by Jonna Kirchhof, taken in the Natural History Museum, Berlin. Figure 2 by Mike Taylor under a CC-BY-4.0 license (https://creativecommons.org/licenses/by/4.0/deed.en), https://svpow.com/2014/06/04/the-field-museums-photo-archives-tumblr-featuring-airbrushing-dorsals/, no changes made.